The Mechanics of Bubble Growth and Rise in Sediments

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LONG-TERM GOALS

Our long term goal is a quantitative, mechanistic and predictive understanding of the dynamics of bubbles and bubble populations in marine sediments. We believe that this information can be used to improve and test acoustic backscatter models for gassy sediments and to better understand the ebullitive flux of methane, an important "greenhouse gas", to the atmosphere.

OBJECTIVES

The overall objective of our work is to understand bubble growth and rise in natural marine sediments. In the first phase of our study (to mid-2003) we demonstrated that bubbles grow and rise in sediments by the mechanism of fracture. The second (current) phase has aimed to develop methods to measure the mechanical properties that control fracture in soft sediment; these properties, i.e., Young's modulus, E, the critical stress intensity factor, K_{1C}, and Poisson's ratio, are not routine measurements and geo-scientists have not developed means for their in situ determination. These properties are needed to solve our evolving models of bubble growth, and indeed have broader significance for understanding the mechanical strength of sediments.

APPROACH

In Linear Elastic fracture Mechanics (LEFM), the geotechnical properties that fully determine fracture strength and the size and shape of resulting cracks are the critical stress intensity factor, K_{1C}, Young's modulus, E, and the Poisson ratio, ν. In laboratory studies we have determined the magnitudes of K_{1C} and E for samples collected at our study site in Cole Harbor, Nova Scotia, and have reported these in Johnson et al. (2002), Gardiner et al. (2003) and Boudreau et al. (2005). However, our laboratory methods for determining K_{1C} and E do not provide sufficient detail to understand the variability of these properties on desired length scales. In addition, we are concerned about the effect of sediment sampling on the physical properties that mediate bubble growth and rise. Consequently we instituted a field program focused on measuring the relevant physical properties *in situ*. To meet this objective, we have developed two new instruments: 1) a sediment instrument package fitted with probes for

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measuring fracture strength (the critical stress intensity factor, K_{1C}) and temperature and 2) an in situ elasticity meter for measuring Young's modulus. Where possible we have ground-truthed the field results with laboratory measurements on samples collected from the same field sites. Concern about the effect of collection of cores for ground-truthing field measurements has led us to develop a sampler that avoids many of the problems of normal core collection. This experimental work is being directed and performed by Bruce Johnson, working with PhD students, Mark Barry and Chris L'Esperance

To better understand the dynamics of methane bubble growth we have developed a finite-element-based mechanistic model for the growth of a gas bubble in sediments. In our model gas is supplied to the growing bubble by methane production from degradation of organic matter. The model treats the sediments as an elastic solid, with bubble growth occurring through a process of elastic expansion and fracture in accordance with the principles of linear elastic fracture mechanics (LEFM) (Johnson et al. 2002, Gardner et al. 2003, Boudreau et al. 2005). The modeling component of the study is being directed and performed by Bernie Boudreau working with PhD student Chris Algar.

WORK COMPLETED

Two different probes were developed for measuring K_{1C}. One of these, a compression-type probe, similar in principle to a cone penetrometer, gave measurements that were more than an order of magnitude too high in sediments with high sand content. A second probe was developed that measures fracture through extensional stress. Laboratory measurements in sediment samples, in gelatin (a fracturing surrogate for sediment) and in potter's clay have shown that results from the extension probe can be interpreted to give K_{1C}, and may also provide results that can be interpreted to give in situ profiles of Young's modulus and sediment yield strength. With the extension probe the value of K_{1C} is determined directly by applying the theory of Linear Elastic Fracture Mechanics (LEFM) without need for adjustable parameters. A sediment platform was developed for deploying the probes in the field. This platform, the "geotechnical property multiprobe *in situ* logger" or GP-MIL, has now been extensively laboratory and field tested.

For both testing the probes and extending the range of fracture toughness data, we have made measurements in the field in a broad range of sediment types. We have also tested the probe in potter's clay, because this material is relatively homogeneous and fractures as an elastic solid. Results from probe measurements of K_{1C} have been compared to results using laboratory engineering methods.

To improve ground-truthing of our measurements, we have developed a new core sampler. This sampler avoids the problems of sample disturbance that alter geotechnical properties when cores are collected using conventional methods.

Also this past year, a new elasticity probe was developed that is able to measure the compressional Young's Modulus of sediments *in situ*. This probe measures the stress required to deform a medium by the shape of a half oblate spheroid (similar to the shape of an injected gas bubble). Young's Modulus is calculated directly from the stress-strain relation measured. Unlike instruments such as a flat dilatometer, the probe requires no calibration.

We have continued our laboratory studies of gas injection into sediment and surrogate sediment samples. In particular, we have developed a method for slow gas injection that better simulates natural processes.

In addition to developing instruments for in situ measurement of K_{1C} and Young's modulus we have developed a laboratory system for measuring the Poisson ratio. These three measurements are the complete set of geotechnical properties necessary for accurately modeling bubble growth in sediments.

RESULTS

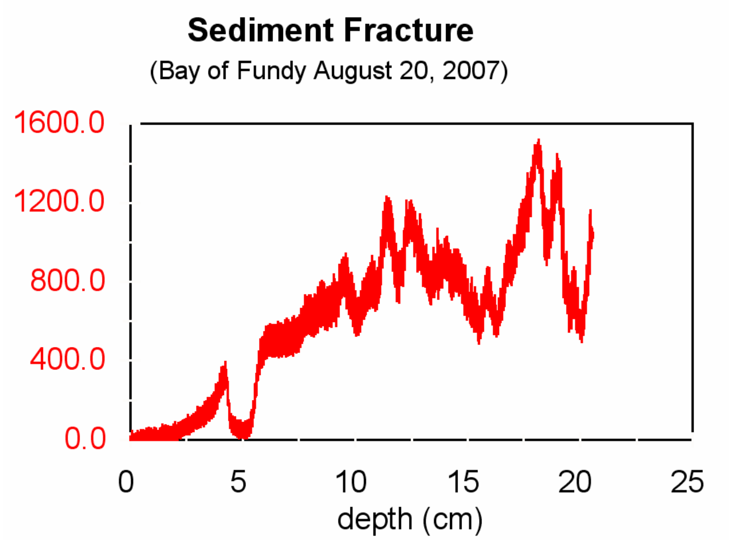

Figure 1: Profile of extensional fracture probe measurements in sediment at Minas Basin, N.S. Note that the line is broad because it is composed of individual fracture peaks. [K_{1C} is 50 N $m^{-3/2}$ just below the sediment – water interface, rising to 600 N $m^{-3/2}$ at 10 cm depth and then peaking at 1500 N $m^{-3/2}$ at 18 cm depth]

We began our field probe study using a compression-type probe, much like a cone penetrometer. However, CT-scan results and measurements of K_{1C} from independent bubble growth studies showed that assumptions about the nature of the crack ahead of the compression probe were often violated and especially when sand was present in the sediment. Noting that bubble growth is extensional, we developed an extension-type probe that gives K_{1C} directly through applying the theory of Linear Elastic Fracture Mechanics (LEFM). Measurements in muddy sediments (below the top unconsolidated region) have given results for K_{1C} that range from less than 100 N $m^{-3/2}$ to about 1500 N $m^{-3/2}$ (Figure 1) – results that compare favorably with laboratory bubble growth measurements. In addition to providing K_{1C}, results from using the extensional probe are also being interpreted to give Young's modulus and yield strength. We have constructed GP-MIL with temperature and compressional probes in addition to the extensional probe.

In laboratory studies we have continued the collaborative work with NRL in which bubble injection into sediment samples is measured by CT scan. Through changes to the gas injector we have achieved a slower growth rate of gas bubbles in sediment samples and a larger range of bubble volumes and consequently have been able to better simulate the natural bubble growth process. Results have shown that sediments over a large range of particle sizes (from silty sand to muddy silt) and porosities (0.40-0.75) deform by elastic fracture under the influence of a growing bubble. Growth typically occurs in the vertical direction, normal to the principal stress. However, CT-scan results show that bubble growth in sediments in which there are numerous heterogeneities present, occurs along planes of weakness that are not normal to the principal stress (Figure 2).

Results of running the finite element model of bubble growth (FEMBG) show that it can reproduce the modeling results described in Gardiner et al. (2003), and in particular, the condition of no-growth which occurs under low source strengths of methane. This condition has now been investigated in more detail using the FEMBG model, and we have found that for a particular value of K_{1C} (the parameter characterizing fracture), there are threshold values of methane production and saturation which must exist in order to raise the internal bubble pressure to the point of fracture. If the source strength or ambient pore-water methane concentration is too low, fracture will not be initiated. Furthermore it was found that the existence of this no-growth condition does not rely on a constant source term, but can also exist in the presence of a depth varying source – a condition that is more consistent with natural sediments.

The 3D nature of the FEMBG model will allow the exploration of a variety of modeling scenarios, such as the depth varying source term just mentioned, which our previous model could not handle due to its symmetry requirements. A few of the problems that this model will be used to examine are: the case of multiple bubbles growing close together, spatial changes in mechanical properties of the sediment, the effect of buoyancy, and various types of forcing, e.g., pressure changes brought on by tides or waves. Finally, another important role of this model will be to solve the transient form of the reaction-diffusion portion of the model and this will allow the testing of the pseudo steady state assumption made in our previous model of bubble growth. Preliminary work using a transient bubble growth model suggests that bubble growth rates occur on a faster time scale than was predicted by previous models. These growth rates are more in line with the tidal cycle time scales under which bubbles in some near shore areas have been observed to grow, e.g., Cape Lookout Bight.

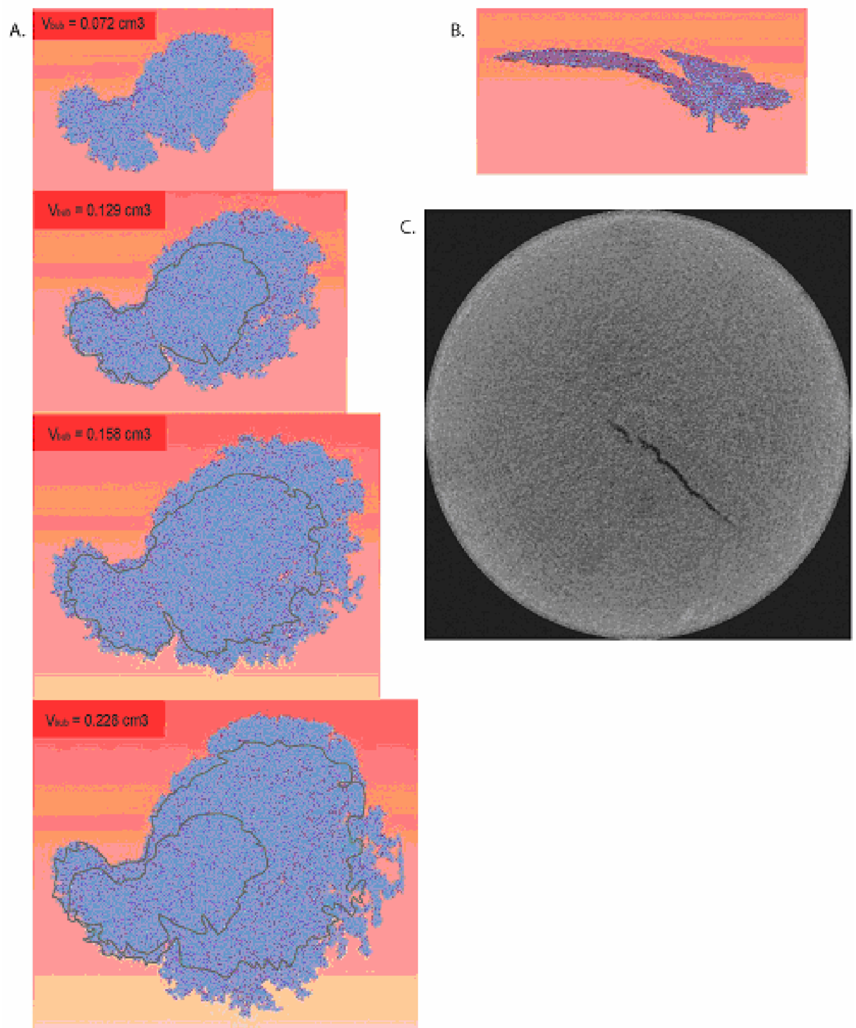

Figure 2: CT scan images of bubble growth in silty sediment from Minas Basin, N.S. Left (A): series of successive images with each showing outline of the bubble in previous images. Note that the bubble volume for each is shown at upper left. Top right (B): side view of injected bubble. Bottom right (C): single CT slice through an injected bubble.
[bubble volumes for CT scan images are 0.72 cm^3, 0.129 cm^3, 0.158 cm^3 and 0.228 cm^3. The bubble grows as an irregular shaped flat inclusion.]

IMPACT/APPLICATIONS

Our results may prove to be highly significant for interpreting acoustic seafloor measurements and estimates of the strength and stability of sediments on the seafloor and in the littoral zone.

RELATED PROJECTS

In collaboration with Peter Jumars (Univ. Maine), and his PhD student Kelley Dorgan, we have been applying the results of our bubble-mechanics work to the problem of the burrowing of infauna. This related project is groundbreaking in that it has identified a new and efficient mode of movement for

burrowing organisms; one that takes far less energy than has been supposed in the past. We have constructed a second GP-MIL for use in Dr. Jumar's laboratory at the University of Maine.

PUBLICATIONS

There are two publications from our collaboration with P. Jumar's group at the University of Maine:

Jumars, Peter A., Kelly M. Dorgan, Lawrence m Mayer, Bernard P. Boudreau, Bruce D. Johnson 2007. Material constraints on infaunal lifestyles: may the persistent and strong forces be with you. Chapter 29; in: Trace Fossils: Concepts, Problems, Prospects. Elsevier Press.

Dorgan, Kelly M., Peter A. Jumars, Bruce D. Johnson, Bernard P. Boudreau 2006. Macro-faunal burrowing: the medium is the message. Oceanography and Marine Biology: An Annual Review, 44, 85-121.